Final Technical Report August 2021
ShakeAlert Cooperative Agreement G19AC00264

Geodetic Monitoring Project Name:
Production of ShakeAlert Real-Time GNSS

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Abstract
CWU point-positioned ~950 GNSS stations within the ShakeAlert footprint and delivered these solutions to all three ShakeAlert centers over the two-year reporting period. 20 PANGA stations were upgraded to Trimble NetR9-RTX receivers, and PPP streams from these receivers were streamed to and archived at CWU. We have implemented metrics of Fastlane processing and conducted analyses of solutions statistics relevant to ShakeAlert and published these in BSSA. RTX-PPP streams were also configured and archived for systematic analysis and comparison to Fastlane positions.

I. Funding Expended
All but $2,809.23 of the project budget as originally proposed was expended.

II. Supported Objectives
Five objectives were proposed, and our accomplishments with regards to those objectives are detailed here.

1. Expand Fastlane Processing to include ~1100 Western US Stations
We increased the number of GNSS stations within the ShakeAlert footprint that we position and stream to ShakeAlert decision centers to ~950 stations. We were unable to reach the full ~1100 stations that we think exist within the footprint for two reasons, detailed below. The 950 stations were positioned with almost no interruptions during the proposal period. Average latency to obtain a position for the 950 stations is 0.52 seconds, as documented in the *Melbourne* et *al*. (2021) BSSA publication listed below. Solution accuracy and completeness is also documented in this publication. We did not reach the full 1100 that we think exist for two reasons. First, CPU limitations: our production system comprises two 30-core computing platforms that we found started to fall behind real-time (consistently less than ~1 second latency) when Fastlane threads exceed more than about 950 stations. As a result, we capped total processing at 950 stations until we can replace the production platform with a new rack-mounted computing system that is already built and which we have continued to test before switching. The new platform has over 500 computing cores, along with another 50 or so dedicated to I/O and internal data stores, so roughly 8x the capacity of our current production system. In the vetting we uncovered various intermittent problems that would show up infrequently within its various subsystems that needed to be resolved. We continue to work towards switching platforms, and this will happen as soon as we can establish that the stability and throughput of the modules that connect to dozens of data and corrections casters, hold the internal data stores for incoming streams and outgoing solutions,

house the broadcasting services, and gather the solutions for analytics, are as good as the current 60-core platform.

The second reason we did not quite reach the full 1100 stations is that the various GNSS networks that span the ShakeAlert footprint change with time, and it requires constant attention to keep casters lists updated. For instance, UNAVCO retired ~130 stations from the NOTA (formerly PBO) array in response to NSF direction, of which ~100 were adopted by other networks and need to be streamed from non-UNAVCO casters. To some extent, this sort of thing happens continuously. We hired Elizabeth Curtiss to work full time to update and finalize lists of stations available from Western US networks and to configure our connections to these networks, which is complete. We are also working with the ShakeAlert Data Working Group to identify existing stations within the ShakeAlert footprint that we are not currently processing. It is our hope that ShakeAlert will provide us a list of stations and corresponding casters that we are expected to position, and that we can simply use that list. In the meantime, we will continue to keep track of the evolving networks.

2. <u>Upgrade 20 stations to have on-board positioning & PANGA Telemetry Hardening</u>
<u>Station Upgrades:</u>
All 20 of the Trimble NetR9 w/ RTX receivers were deployed into the PANGA network. PANGA has now upgraded a total of 75 GNSS receivers (out of 220) to onboard PPP processing, of which 30 were completed during this project period. Onboard PPP solutions from these 75 sites stream directly to CWU as GSOF-formatted strings, where we archive them for analytics.

Total onboard PPP-enabled PANGA upgrades to date:

ARLI	48.17	-122.14	Arlington	WA
BDRY	48.99	-117.35	Boundary Lake	WA
BELI	48.76	-122.48	Bellingham	WA
BILS	47.54	-124.25	Queets	WA
COUP	48.22	-122.69	Coupeville	WA
CSKI	47.38	-122.24	Kent	WA
CULM	47.98	-121.69	Spada Lake	WA
CUSH	47.42	-123.22	Lake Cushman	WA
DANP	46.28	-119.28	Richland	WA
DEEJ	47.47	-123.93	Amanda Park	WA
DVPT	47.66	-118.15	Davenport	WA
ELSR	47.50	-122.76	Bremerton	WA
ENUM	47.21	-121.96	Enumclaw	WA
GLWD	46.02	-121.29	Glenwood	WA
GOLY	45.84	-120.81	Goldendale	WA
GRMD	46.80	-123.02	Grand Mound	WA
HAHD	47.29	-121.79	Palmer	WA
KOOT	47.77	-116.81	Couer D'Alene	ID
LINH	47.00	-120.54	Ellensburg	WA
LSIG	47.70	-121.69	Tolt	WA
MKAH	48.37	-124.59	Makah	WA
NINT	47.50	-121.80	North Bend	WA
OCEN	46.95	-124.16	Ocean Shores	WA

OLAR	46.96	-122.91	Olympia	WA
PDXA	45.60	-122.61	Portland	OR
PFLD	47.90	-122.28	Everett	WA
PTAA	48.12	-123.49	Port Angeles	WA
QMAR	47.78	-120.97	Stevens Pass	WA
SAMM	47.54	-122.03	Issaquah	WA
SMAI	47.52	-122.35	Seattle	WA
SPRG	47.31	-117.98	Sprague	WA
SSHO	47.68	-122.32	Seattle	WA
TACO	47.23	-122.47	Tacoma	WA
TUMW	46.98	-122.91	Tumwater	WA
TWSP	48.37	-120.12	Twisp	WA
WEBG	45.78	-122.56	Battleground	WA
BBAY	48.90	-122.77	Birch Bay	WA
BLYN	48.02	-122.93	Blyn	WA
CABL	42.84	-124.56	Port Orford	OR
CATH	46.20	-123.37	Cathlamet	WA
CHCM	48.01	-122.78	Chimacum	WA
CHZZ	45.49	-123.98	Tillamook	OR
COUG	46.06	-122.26	Cougar	WA
CRBN	47.08	-122.05	Carbonado	WA
CROK	46.27	-122.91	Castle Rock	WA
FARW	47.64	-117.65	Spokane	WA
GHCL	46.95	-123.80	Grays Harbor	WA
GORG	47.09	-119.85	George	WA
GRCK	48.14	-117.66	Grouse Creek	WA
GTPS	42.43	-123.30	Grants Pass	OR
IDNP	45.94	-116.12	Grangeville	ID
JOBO	48.56	-122.44	Edison	WA
KENI	46.20	-119.16	Kenniwick	WA
KLSP	48.35	-117.27	Usk	WA
LFLO	43.98	-124.11	Florence	OR
LPSB	44.05	-123.09	Eugene	OR
LTAH	47.28	-117.16	Latah	WA
LWCK	46.28	-124.05	Ilwaco	WA
NWBG	45.30	-122.98	Newberg	OR
OLMP	47.04	-122.90	Olympia	WA
ONAB	44.51	-124.07	Ona Beach	OR
P064	47.97	-123.49	Hurricane Ridge	WA
PKWD	46.60	-121.68	Packwood	WA
PNNL	48.08	-123.05	Sequim Bay	WA
PYLP	47.19	-122.26	Pyallup	WA

RDL2	42.95	-123.36	Riddle	OR
REED	43.70	-124.11	Reedsport	OR
RKD1	48.96	-119.41	Oroville	WA
RSBG	43.24	-123.36	Roseburg	OR
RYMD	46.68	-123.73	Raymond	WA
SEAS	45.98	-123.92	Seaside	OR
SEQM	48.09	-123.11	Sequim	WA
TILL	45.46	-123.83	Tillamook	OR
VCWA	45.62	-122.52	Vancouver	WA
YCS2	46.94	-122.59	Yelm	WA
YONC	43.63	-123.30	Drain	OR

2b. Redundant Telemetry
We are expanded the proposed stations to have two separate data communication systems for PANGA receivers, one based on dedicated cellular (CDMA) modems and the other on low-power satellite transmission system (VSAT).

CDMA communications
During this project, we have continued to install redundant cellular data communications at coastal sites from northern Washington to southern Oregon, pursuant to ShakeAlert priorities. In addition, we are also adding cellular communications to all GNSS stations co-located with strong ground motion seismometers. These station-direct data streams are all power backed with additional battery banks (small overlain yellow circles in Figure 1, below), and operated under a Broadband Priority contract with the cellular carrier. PANGA now manages 40 cellular data plans.

As proposed, we have installed an additional 15 direct cell communications at strategically located sites and GNSS/SGM collocated ShakeAlert sites. In total, this brings us to 38 direct data streams from GNSS sites that either have, or are slated to have, collocated strong ground motion sensors.

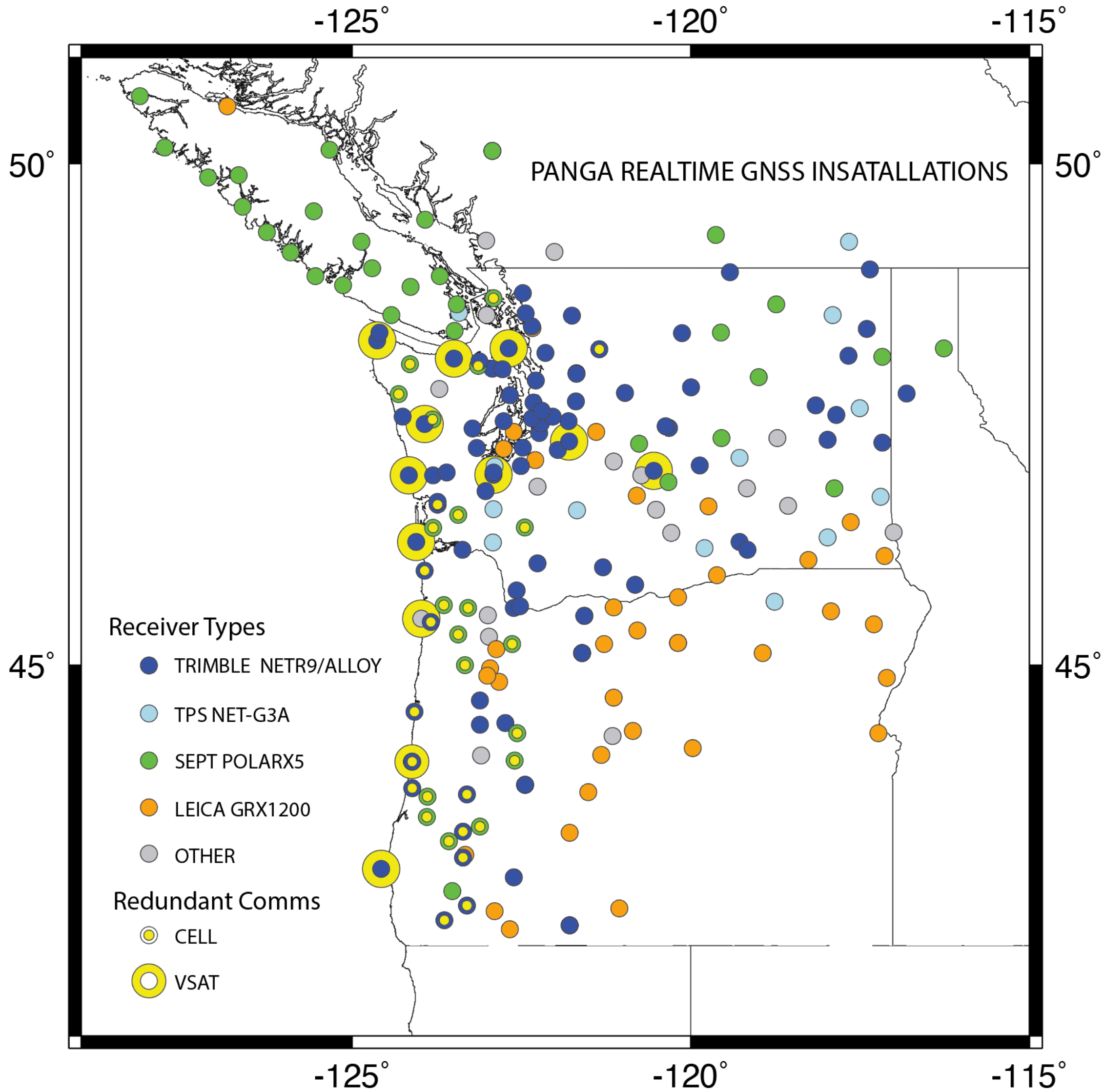
Data hardening cellular redundant telemetry installed to date:

SITE	CITY	STATE	LAT	LON	SGM
BBAY	Birch Bay	WA	48.90	-122.77	N
BLYN	Blyn	WA	48.02	-122.93	N
CABL	Port Orford	OR	42.84	-124.56	Y
CHZZ	Tillamook	OR	45.49	-123.98	Y
DISC	Ellensburg	WA	47.00	-120.54	N
GTPS	Grants Pass	OR	42.43	-123.30	N
LFLO	Florence	OR	43.98	-124.11	N
ONAB	Ona Beach	OR	44.51	-124.07	Y
P064	Hurricane Ridge	WA	47.97	-123.49	N
P191	Selma	OR	42.28	-123.63	Y
P366	Dean Mtn	OR	43.61	-123.98	Y
P369	Roseberg	OR	43.14	-123.43	Y
P371	Glide	OR	43.36	-123.06	Y

P376	Salem	OR	44.94	-123.10	Y
P377	Springfield	OR	44.05	-122.89	Y
P378	Labonon	OR	44.53	-122.93	Y
P397	Naselle	WA	46.42	-123.80	Y
P400	Lake Quinault	WA	47.51	-123.81	Y
P402	Forks	WA	47.77	-124.31	Y
P403	Beaver	WA	48.06	-124.14	Y
P405	Tillamook	OR	45.63	-123.64	Y
P406	McMinville	OR	45.19	-123.15	Y
P411	Forest Grove	OR	45.54	-123.16	Y
P412	Mulino	OR	45.22	-122.59	Y
P415	Raymond	WA	46.66	-123.73	Y
P425	Toldeo	WA	46.45	-122.85	Y
P436	Sequim	WA	48.05	-123.13	Y
P439	East Sound	WA	48.71	-122.91	Y
P442	Darington	WA	48.26	-121.62	Y
P732	Coos Bay	OR	43.39	-123.89	Y
PTAA	Port Angeles	WA	48.12	-123.49	N
RDL2	Riddle	OR	42.95	-123.36	N
RDTP	Liberty	WA	47.27	-120.76	N
REED	Reedsport	OR	43.70	-124.11	Y
RSBG	Roseburg	OR	43.24	-123.36	N
SC03	Mt. Olympus	WA	47.82	-123.71	Y
SEAS	Seaside	OR	45.98	-123.92	Y
TILL	Tillamook	OR	45.46	-123.83	Y
YONC	Drain	OR	43.63	-123.30	N

Data Hardening: VSAT direct-satellite communications

We have upgraded all our VSAT stations in WA and OR with new Nanometrics-supplied data transfer firmware. This update allows each site to stream RTCM3-formatted strings, and also should allow simultaneous streaming of onboard PPP solutions alongside the full RTCM-formatted raw satellite observables. Additionally, we hope these updates will allow us to increase the number of sites without incurring extra costs or adding data latency. This past year we also constructed another VSAT to fill a gap on the Oregon coast (large yellow circles below).



August 2021 PANGA real-time receiver type with redundant telemetry delineated in yellow.

3. Implement metrics for real-time processing CWU Fastlane Positioning

We have implemented Prometheus solutions logging along with Grafana analytics on all Fastlane solutions produced during the last year. Specifically, we have built up logging the following fields: Observables: count, latency (receiver to Prometheus), latency (receiver to Fastlane input redis); Ephemerises: count received, IODE, IODC; Satellite clock corrections; Satellite orbit corrections; Fastlane solutions epoch, count received, ENU displacement, ENU error, Chi-squared, cycle slips; latencies of positioning, filtering, processing, and time of arrival in Prometheus. Total logged information is roughly 100Gb per month of logged solutions. We have been systematically analyzing these data to quantify accuracy, completeness and the different latencies. This effort has largely consisted of writing Python programs that interface with Grafana and Prometheus, and are shown below:

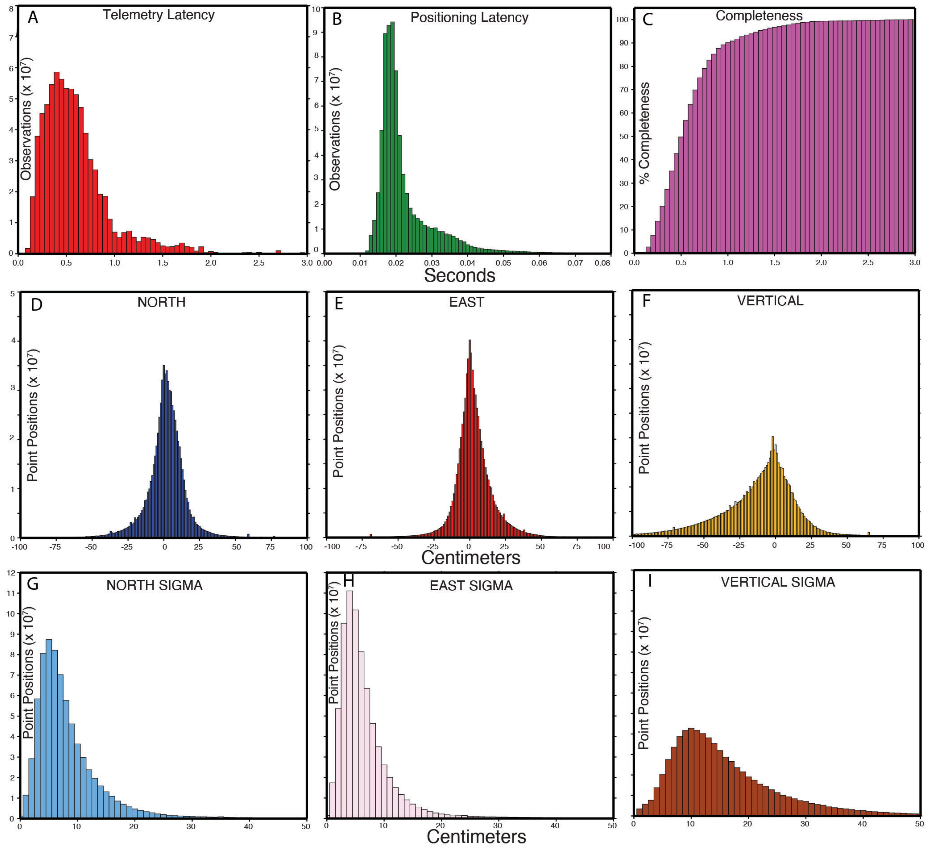


Figure 7. Fastlane PPP performance analytics measuring latency, completeness and accuracy for 1270 globally-distributed stations positioned during a typical one week period (July 7-14 2020), totaling ~900 million solutions. (A) Telemetry latency is the time of arrival into the observables decoder (Figure 3) minus observation of time of that epoch. (B) Positioning latency is time of arrival of solution into solutions key-value store minus time of arrival observables key-value store. (C) Completeness is defined as number of solutions with acceptable covariances through time divided by percentage of maximum number of possible solutions per time (86,400 solutions per 24 hours per receiver for 1-s epochs). (D-F) North, East and Vertical position difference at each epoch from nominal position. (G-I) North, East and Vertical positions formal errors.

We will continue to pull and assemble metrics that are currently being determined by the Geodetic Data Products Committee, with whom we are working, to best quantify metrics most useful to ShakeAlert.

4. Compare CWU Fastlane positions with onboard PPP Onboard PPP Solutions Logging

We have implemented capturing onboard PPP solution streams as they arrive direct to CWU. Onboard PPP solutions are parsed and stored as a JSON record to a file, with one file per stream. At the end of each GPS week those streams roll over to new files, and a single HDF5 archive file is made of the previous weeks' files. As with Fastlane, we have not yet begun systematically analyzing the accuracy, completeness and latency of these GSOF PPP streams. We do note some gaps and record breakage for some sites, but these have lessened with time as Trimble has improved their global system. We were not able to write the analysis tools needed to generate completeness percentages or latency, but continue to work towards it. We intend to undertake both the Fastlane and onboard PPP analyses at the same time so that we can treat them equally.

5. Stream solutions to ShakeAlert Centers

We have streamed, with almost no interruption over the two years of the project, all rt-GPS solutions to the three ShakeAlert centers at U. Washington, Berkeley, and Caltech. The two interruptions, each comprising only a few minutes, were caused by failures in the IGS GPS satellite clock corrections service. During these interruptions, our solutions streams nonetheless flowed uninterrupted to the ShakeAlert centers, but had poor resolution, of several meters scatter instead of several cm scatter. Other than the IGS stream interruptions, there were no other breaks to CWU's Fastlane stream flow to ShakeAlert centers.

Project Data Management Plan
Our data management practices conform to the *Geodetic Network Standards and Procedures*. Metadata for the stations PANGA is solely responsible for are available in IGS site log format here: http://www.panga.org/data_ftp_pub/sites/logs/ . All real-time solutions are streamed to several USGS cooperative networks and the NEIC, and archived locally. Post-processed time series are made available via the PANGA website at www.panga.org.

III. Problems encountered
COVID-19 and CWU's move to only remote work hindered, but did not stop, progress. The PANGA group worked from home for much of 2020 and 2021, and fieldwork stopped for most of the spring. Requisitions were processed slower and delivered with greater delays. By fall of 2020 we were back in the office working as normal. Fieldwork resumed, and all our commitments to this project fulfilled.

The National Geodetic Survey model for Zephyr 3 (TRM115000.00) antennas with tall SCIGN domes (SCIT) was found to be in error over fall of 2019. The robotic model calculated was relative to the wrong antenna reference point (ARP). Corrections utilizing this model were subsequently off (in some cases by a couple cm). The model was removed from the NGS & IGS systems and sent all the equipment back for an updated model. This process was also delayed due to the COVID-19 crisis but the new model has been completed, accepted and published by the IGS and NGS. We are now currently replacing the domes on affected sites: BDRY, ARLI, DMND, GTPS, LTAH, LWCK, PTAA, REED, RKD1, RSBG, SEAS, XANE, and YONC. Once completed, we will reprocess these data.

IV. Publications this project:
1. 2021 Melbourne, T.I, Szeliga, W., Scrivner, W., amd Santillan, M., Global Navigational Satellite System Seismic Monitoring, *Bull. of the Seismo. Soc. of Am., 111(3),* doi:10.1785/0120200356
2. Toward Near-Field Tsunami Forecasting Along the Cascadia Subduction Zone Using Rapid GNSS Source Models, Amy L. Williamson, Diego Melgar, Brendan W. Crowell, Diego Arcas, Timothy I. Melbourne, Yong Wei, and Kevin Kwong 10.1029/2020JB019636
3. Noise Characteristics of Operational Real-Time High-Rate GNSS Positions in a Large Aperture Network, Diego Melgar, Brendan W. Crowell, Timothy I. Melbourne, Walter Szeliga, Marcelo Santillan, and Craig Scrivner Journal of Geophysical Research: Solid Earth doi: 10.1029/2019JB019197
4. 25-Second Determination of 2019 Mw 7.1 Ridgecrest Earthquake Coseismic Deformation, Timothy I. Melbourne, Walter M. Szeliga, V. Marcelo Santillan, and Craig W. Scrivner., *Bulletin of the Seismological Society of America Volume XX, Number XX – 2020* doi: 10.1785/0120200084
5. Seismic Sensors in Orbit, Timothy I. Melbourne, Diego Melgar, Brendan W. Crowell, and Walter M. Szeliga, *EOS Earth & Science Space News*, Volume 101, Number 1, 2020
6. Real-Time High-Rate GNSS Displacement Performance Demonstration during the 2019 Ridgecrest, California, Earthquakes, Diego Melgar, Timothy I. Melbourne, Brendan W. Crowell, Jianghui Geng, Walter Szeliga, Craig Scrivner, Marcelo Santillan, and Dara E. Goldberg, Seismological Research Letters Volume XX, Number XX – 2020 doi: 10.1785/0220190223